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TECHNICAL NOTE

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EFFECT OF A VARIABLE-GEOMETRY DIFFUSER ON THE OPERATING CHARACTERISTICS OF A HELIUM TUNNEL DESIGNED FOR A MACH NUMBER IN EXCESS OF 20

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SUMMARY

An experimental investigation has been conducted in a 3-inch helium tunnel equipped with a conical nozzle and operating at a Mach number of 20 to determine the effectiveness of variable-geometry supersonic diffusers in decreasing the overall pressure ratio required to maintain flow. Four diffuser entrance wall lengths were investigated. The results indicate that the overall pressure ratio required to maintain flow, if a constant-area diffuser is used, could be decreased 34 percent by utilizing an optimum combination of diffuser entrance wall length and diffuser entrance wall angle. For this combination, only 61 percent of test-section pitot pressure could be recovered by the diffuser.

INTRODUCTION

Diffusers are used in supersonic wind tunnels primarily to decrease the overall pressure ratio necessary to maintain supersonic flow and may also be used to decrease starting-pressure-ratio requirements. In intermittent blowdown tunnels this decrease in pressure ratio lengthens the operating time, and in continuous running tunnels it permits a reduction in the power required to operate the tunnel.

In the inviscid case, the decrease in pressure ratio is accomplished by decelerating the flow through a series of oblique shocks in the convergent section of the diffuser. The Mach number in front of the normal shock is therefore smaller than the test-section Mach number and the losses across the normal shock are correspondingly reduced. At extremely high Mach numbers, however, this design philosophy might not prove very effective since, for convenient entrance wall lengths, the relatively small shock angles would allow few, if any, wave reflections from the opposite wall.

In the actual case, losses due to viscosity significantly affect diffuser performance. Since the magnitude of these viscous losses are, at best, difficult to predict, experiment has been relied upon to provide the information necessary for the design of efficient diffusers for supersonic wind tunnels. Typical examples of such experimental investigations are reported in references 1, 2, 3, and 4. In the hypersonic Mach number range, where viscous effects become increasingly severe, the effect of diffusers on tunnels operating at Mach numbers up to 9.6 is discussed in reference 5. Further increases in Mach number, with air used as a test medium, produce very difficult design problems because of the high temperature and pressure problems associ- L
ated with such facilities. These design problems may be avoided by 7
using helium as a test medium because its use permits the generation 8
of large hypersonic Mach numbers without the attendant high-temperature 3
problems. Furthermore, the pressure ratio required to produce a given Mach number is considerably less than that required for air. For example, the total pressure ratio across a normal shock at a Mach number of 20 in air is 9,500 ($\gamma = 7/5$), whereas for helium this ratio is only 350 ($\gamma = 5/3$).

Inasmuch as no available information exists at the present time concerning the performance of diffusers in wind tunnels operating at Mach numbers above 10, an investigation has been undertaken to study the effect of variable-geometry diffusers on the pressure-ratio requirements of such a facility. The tests were conducted at a Mach number of approximately 20 in a 3-inch-diameter helium tunnel having a conical nozzle and equipped with two-dimensional variable-geometry diffusers. (This tunnel is a 0.137-scale pilot model of a facility under construction at the Langley Research Center.) The diffuser entrance wall length varied from 8.81 inches to 20.50 inches. Tests were made at a stagnation pressure of 2,015 psia; the corresponding Reynolds number was 2.27×10^6 based on the 3-inch diameter of the test section.

SYMBOLS

A_1 test-section area, sq in.

A_2 diffuser minimum area, sq in.

M Mach number

p nozzle exit static pressure, psia

p_t stagnation pressure, psia

$p_{t,e}$ diffuser exit pitot pressure, psia

p_t' pitot pressure measured in nozzle exit plane, psia

R Reynolds number based on test-section diameter

r radial distance from tunnel center line, in.

γ ratio of specific heats

η efficiency, $\dfrac{p_t}{p_{t,e}} = \left(\dfrac{p_t}{p}\right)^{1-\eta}$

θ supersonic-diffuser entrance wall angle, deg

APPARATUS

General Description of Tunnel

The tests were conducted in a 3-inch-diameter helium tunnel. A sketch of the interior dimensions of this facility is shown in figure 1. The conical nozzle has a 0.090-inch-diameter throat and expands with a semidivergence angle of 5° up to the constant 3-inch-diameter test section. (This area ratio should provide a Mach number of 26 at the nozzle exit plane based on theoretical one-dimensional area-ratio calculations.) A round-to-square straight-line-element transition section was located downstream of the test section. A model support strut and sting was mounted in this section. For the present tests the model consisted of a 3-tube pitot-pressure rake (fig. 1) whose maximum frontal area (including the support strut) was equal to 7.10 percent of the test-section area. The transition section was followed by the two-dimensional variable-geometry diffuser which, in turn, was joined to a subsonic-diffuser transition section that led to a 6-inch-diameter pipe. A single rake consisting of five equally spaced total-pressure tubes was mounted vertically in the exit pipe as shown in figure 1.

The variable-geometry diffuser consisted of two pairs of plane, hinged plates which were supported between the parallel sidewalls. The hinge-point locations of these plates are shown in figure 1. The plates were driven to preselected positions by pneumatically driven pistons. Figure 2 shows the variation of diffuser area ratio A_2/A_1 with entrance wall angle θ for the four wall lengths of interest. The shortest two of the four walls have sliding-plate arrangements to make up for the difference in length when the walls were deflected.

Entrance wall lengths of 17.57 inches and 20.50 inches were made available simply by turning the diffuser-plate assembly around. A low pressure was maintained on the outside of the diffuser plates by venting the chamber enclosing the diffuser to the tunnel vacuum system. Close tolerances were maintained between the movable plates and the sidewalls to hold any possible leakage to a minimum.

Helium was supplied to the stagnation chamber from storage tanks and was available at pressures up to 3,000 psi. Four variable-speed, rotary-vane-type vacuum pumps were used to maintain a starting exit pressure on the order of 1 psia.

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Flow Calibration

The Mach number distribution in the nozzle and test section was determined by pitot tube surveys. Pitot pressures for the calibration were measured by 16-inch Bourdon compound gages which provided an accuracy of about 1 percent at a Mach number of 20. Longitudinal Mach number surveys are shown in figure 3. A lateral variation in Mach number of less than 1 existed at the exit of the nozzle in the isentropic core of the flow and was considered to be of sufficient uniformity for the present investigation.

Method of Operation

Supersonic flow was established with the diffuser walls undeflected; then the walls were closed to the preselected setting. This procedure was employed because the minimum diffuser area permissible for starting is greater than the diffuser area ratio at which optimum pressure recovery is achieved.

The diffuser exit pressure was permitted to increase until the pressure ratio across the system was insufficient to support supersonic flow and the flow broke down. Oscillograph records were obtained of the pitot pressure in the test section and the exit pitot and static pressures during the entire test. The exit pitot pressure used in the determination of overall pressure ratio required to maintain supersonic flow was obtained from a numerical average of the pressures recorded by the oscillograph at the instant at which the flow broke down.

Instrumentation

Test-section pitot pressures were measured by 15-psi NACA miniature electrical pressure gages. Pressures registered by the five exit pitot tubes and one exit static-pressure orifice were measured by 0- to 5-psia pressure gages. The output of these gages was recorded by an oscillograph. The accuracy of the recording system was approximately 1 percent of full scale. Stagnation pressure was measured by a 16-inch Bourdon gage having an accuracy of ±5 psi.

RESULTS AND DISCUSSION

Pressure Ratio Required to Maintain Supersonic Flow

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The effect of diffuser area ratio on the overall pressure ratio necessary to maintain flow is shown in figure 4 for each entrance wall length. Minimum permissible operating area ratios are indicated on the separate plots and varied from approximately 25 to 28 percent of the test-section area depending on the entrance wall length. Scatter in the data may be observed to increase somewhat for area ratios less than the optimum and is probably associated with random boundary-layer separation from the diffuser walls.

The oscillograph records indicated that test-section pitot pressures were not affected by the diffuser setting. This would infer that the combination of a relatively long transition section upstream of the supersonic diffuser and the favorable pressure gradient produced by the conical nozzle effectively eliminated any pressure feedback through the thick wall boundary layer which could thicken the boundary layer and thus diminish the effective nozzle expansion angle.

A comparison of the results presented for the different entrance wall lengths in figure 4 is shown in figure 5. It may be observed in figure 5 that a pressure ratio of 880 is necessary to maintain supersonic flow at a diffuser area ratio of unity. As the second minimum area is diminished, the pressure ratio required to maintain the flow decreases until an optimum area ratio is reached. Further reductions in area ratio require higher pressure ratios to maintain the flow. The overall pressure ratio required to maintain supersonic flow, with a constant-area diffuser, was reduced 34 percent by utilizing the optimum area ratio for the shortest entrance wall tested.

Figure 6 shows the effect of supersonic-diffuser entrance wall angle θ on the pressure ratio required to maintain flow for the four wall lengths used in these tests. An envelope curve has been faired through the minimum pressure-ratio values obtained for each configuration. It appears from the results shown in figure 6 that further reductions in overall pressure ratio for the present tunnel configuration cannot be effected by either decreasing the entrance wall length or increasing the wall angle θ.

Effect of Reynolds Number on Diffuser Performance

Because of vacuum-system and stagnation-pressure limitations, significant variations in Reynolds number could not be effected. A few tests were made, however, at a stagnation pressure of 1,515 psia $\left(R = 1.70 \times 10^6\right)$ and these results are compared in figure 7 with similar data obtained with the 8.81-inch wall length at $p_t = 2{,}015$ psia $\left(R = 2.27 \times 10^6\right)$. The reduction in Reynolds number had no appreciable effect on diffuser performance and the small reductions in overall pressure ratio shown in figure 7 may be attributed to the reduction of the test-section Mach number effected by reducing the stagnation pressure. A similar trend was observed to occur at $M = 6.86$ in the tests of reference 1.

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In an effort to simulate higher Reynolds numbers and to insure the development of fully turbulent boundary-layer conditions, a 1-inch-wide transition strip consisting of 0.005- to 0.008-inch-diameter aluminum-oxide grains was applied 3/4 inch downstream of the nozzle throat. The stagnation pressure for these tests was 2,015 psia. The results are shown in figure 8 and indicate that, within the accuracy of the data, no significant improvements in diffuser performance occurred.

Comparison of Present Results With Data From Other Wind-Tunnel Facilities

It is of interest to compare the present results at Mach numbers on the order of 20 with data previously obtained at Mach numbers less than 10 in tunnels equipped with variable-geometry diffusers. It should be noted, however, that such a comparison presents difficulties since, in general, no two wind-tunnel—diffuser combinations are geometrically similar.

The pressure with which the designer is ultimately interested is the exit pressure which must be maintained in order to provide a sufficient overall pressure ratio to obtain the desired Mach number for a given stagnation pressure. As was pointed out briefly in the introduction, the present results obtained in helium are not directly comparable with similar data obtained in air. This arises, of course, from the fact that the ratios of specific heats for air and helium are 7/5 and 5/3, respectively, at standard conditions. One method by which the data obtained in air and in helium may be compared is to determine the percent reduction in overall pressure ratio required to maintain supersonic flow achieved by the use of a variable-geometry diffuser. This was accomplished by comparing the required pressure ratio at a diffuser area ratio of 1 with the lowest pressure ratio obtained by the use of a variable-area-ratio diffuser. (In most cases, for example, references 1, 3, and 5, the diffuser area ratios did not extend to unity. For some of these cases the data were readily extrapolated to an area ratio of 1 since the variation of pressure ratio with diffuser area ratio is approximately linear for area ratios approaching 1.) The results of the comparison of data obtained from references 1, 3, 5, 6, and 7 with those obtained in the present investigation are shown in figure 9 as the variation of percent reduction of overall pressure ratio with test-section Mach number. Considerable scatter is evident in this figure and indicates that, for some investigations, optimum-geometry diffusers were not found. In addition, wide variations in Reynolds number and tunnel geometry might also be contributing factors to the scatter. Maximum reductions in overall pressure ratio of about 70 percent occurred at Mach numbers near 7. Such reductions were achieved, however, with no model or other obstruction in the test section. For the present tests made in helium at a Mach number of 20, a reduction in overall pressure ratio of 34 percent was achieved. This reduction compares favorably with the 46-percent reduction obtained in the tests of reference 1 at $M = 6.86$ with a model and support strut mounted upstream of the diffuser. The insertion of a model and support strut upstream of the supersonic diffuser has been shown to dimininsh the reduction in required pressure ratio. (See, for example, refs. 1 and 3.) The data shown in figure 9 indicate that these blockage effects apparently become more pronounced at the higher Mach numbers. It might be pointed out in conjunction with the foregoing remarks on the effects of a model and support upstream of the diffuser that the effect on diffuser performance of the relatively long transition section upstream of the diffuser entrance in the 3-inch tunnel is unknown. However, in view of the current trend in hypersonic-tunnel design toward conical and three-dimensional contoured nozzles (as opposed to the conventional two-dimensional contoured nozzles used for lower Mach number supersonic tunnels), the results obtained in the present investigation, wherein a conical nozzle in conjunction with a two-dimensional, variable-geometry diffuser was used, are felt to provide realistic design information for extremely high Mach number helium facilities, particularly those equipped with conical nozzles.

The exit total pressures obtained in several facilities, expressed in terms of test-section pitot pressure, are compared in figure 10. The data shown in this figure indicate that pressures in excess of two times test-section pitot pressure can be recovered at Mach numbers near $M \approx 8$ by the use of variable-geometry diffusers. For the present tests at $M = 20$ in helium, only about 61 percent of the test-section pitot pressure is recovered. The results presented in figure 10 are considered conservative for the present tests and those of reference 5. This arises from the fact that for both investigations a streamwise Mach number gradient existed in the test section. In each case, however, the pitot pressure was measured at the nozzle exit and, thus, conservative values of p_t' were obtained.

Another term frequently used to compare results from various diffusers is the efficiency η, which may be defined as

$$\frac{p_t}{p_{t,e}} = \left(\frac{p_t}{p}\right)^{1-\eta}$$

where η is a measure of the deviation from isentropic compression. The development of an equivalent expression for η is given in reference 8.

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A comparison of the efficiencies of various diffuser systems for Mach numbers up to 20 is presented in figure 11. As a result of the difference in the ratio of specific heats the data for air and helium may not be directly compared. This is illustrated by the two theoretical curves computed for a normal shock compression. The data obtained in air below $M \approx 10$ are observed to fall roughly parallel to and somewhat higher than the theoretical normal-shock curve for air. On the other hand, the present results at $M = 20$ are somewhat below the normal-shock curve for helium. In either case, it appears that diffuser efficiencies less than 0.50 can be expected for Mach numbers above 12.

CONCLUDING REMARKS

A variable-geometry-diffuser investigation has been conducted in a 3-inch helium tunnel equipped with a conical nozzle and operating at a Mach number of 20. At a diffuser area ratio of unity this facility required an overall pressure ratio of 880 to maintain supersonic flow in the test section. The shortest diffuser entrance wall tested (8.81 inches) allowed a 34-percent reduction in overall pressure ratio at the optimum area ratio. The data indicated that further reductions in wall length would not produce significant reductions in the pressure ratio required to maintain the flow. The small variations in Reynolds number which were effected in these tests had no significant influence on the overall pressure ratios. Severe viscous losses limited the pressure recovery of the diffuser to about 61 percent of the pitot pressure behind a normal shock at the test Mach number of 20.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., December 8, 1959.

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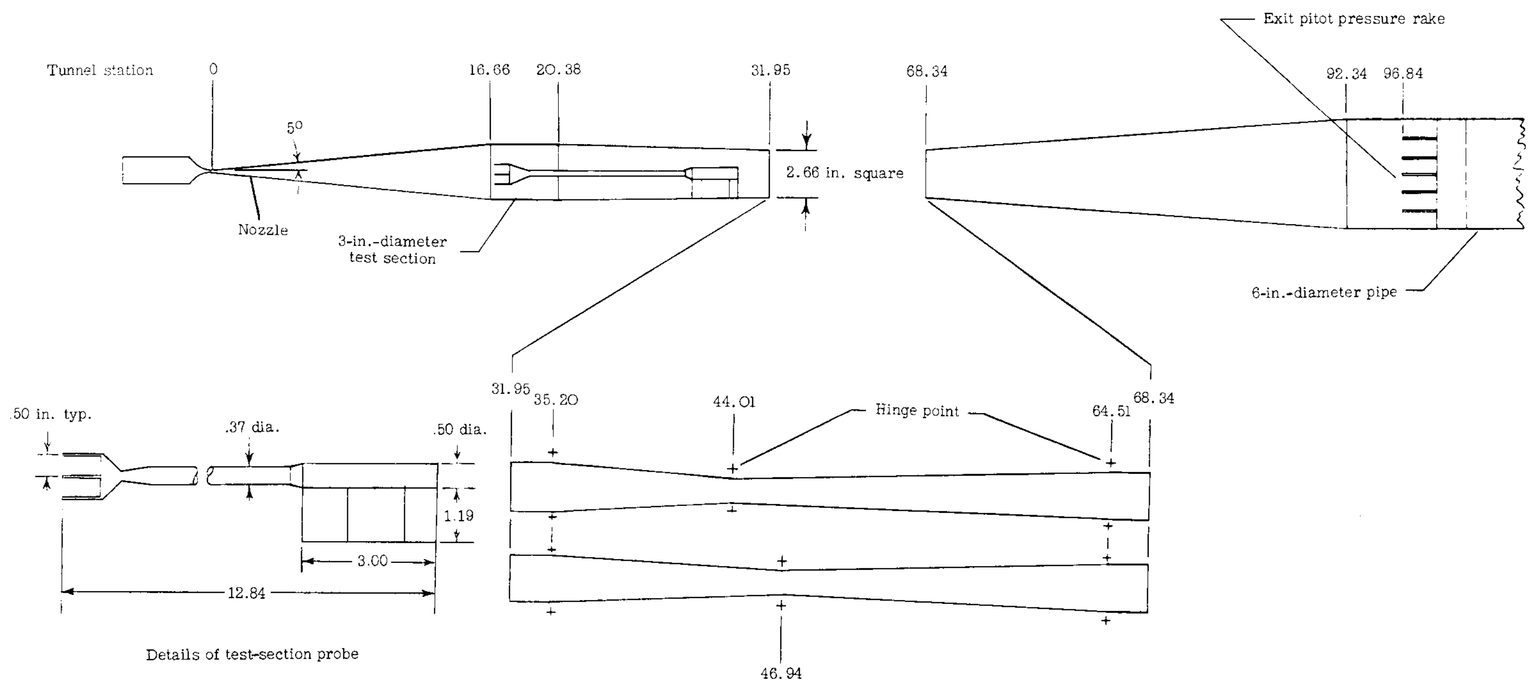

Figure 1.- Sketch of interior dimensions of tunnel, including diffuser configurations. All dimensions are in inches.

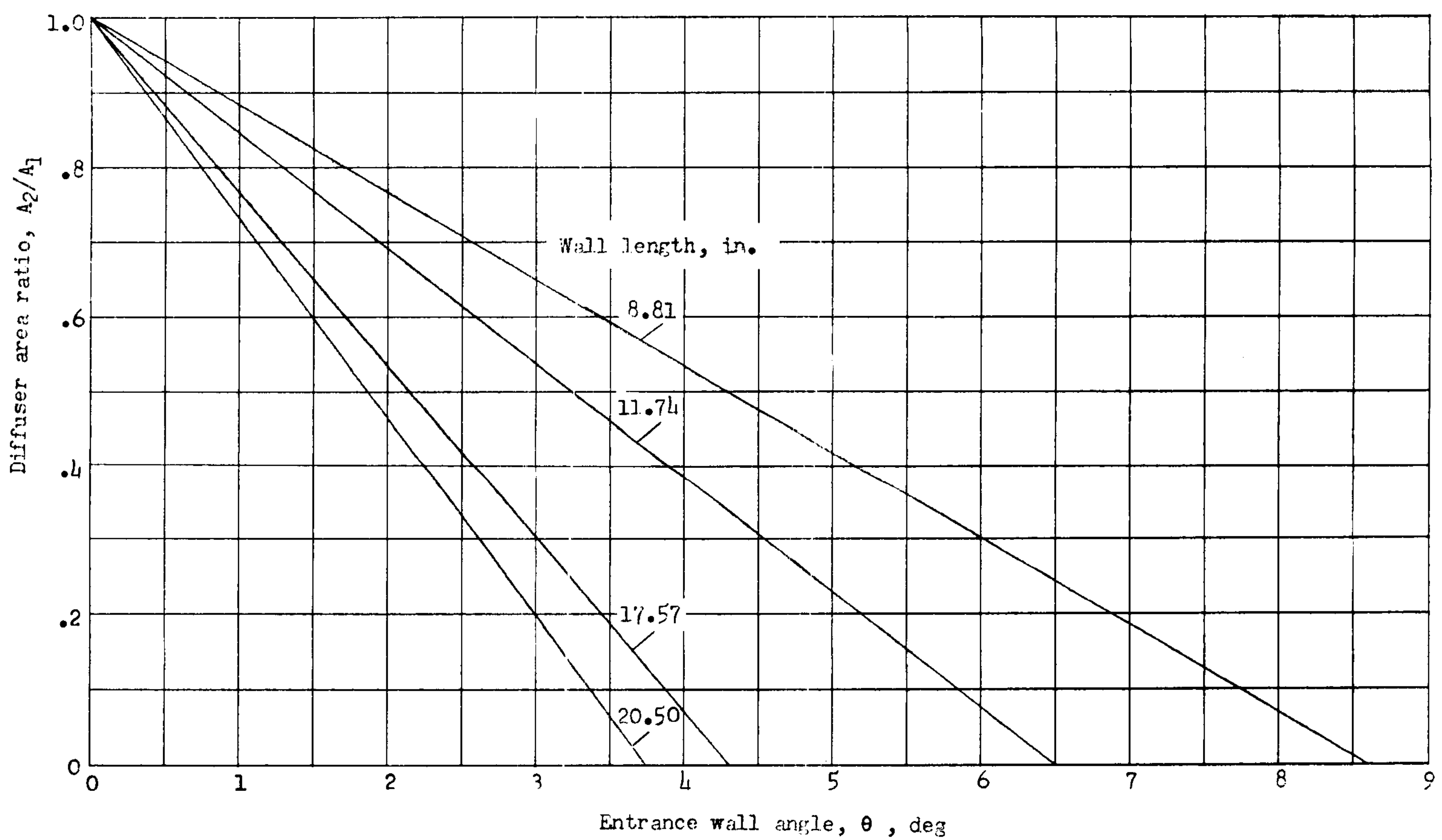

Figure 2.- Diffuser area ratio as a function of entrance wall angle for the four wall lengths.

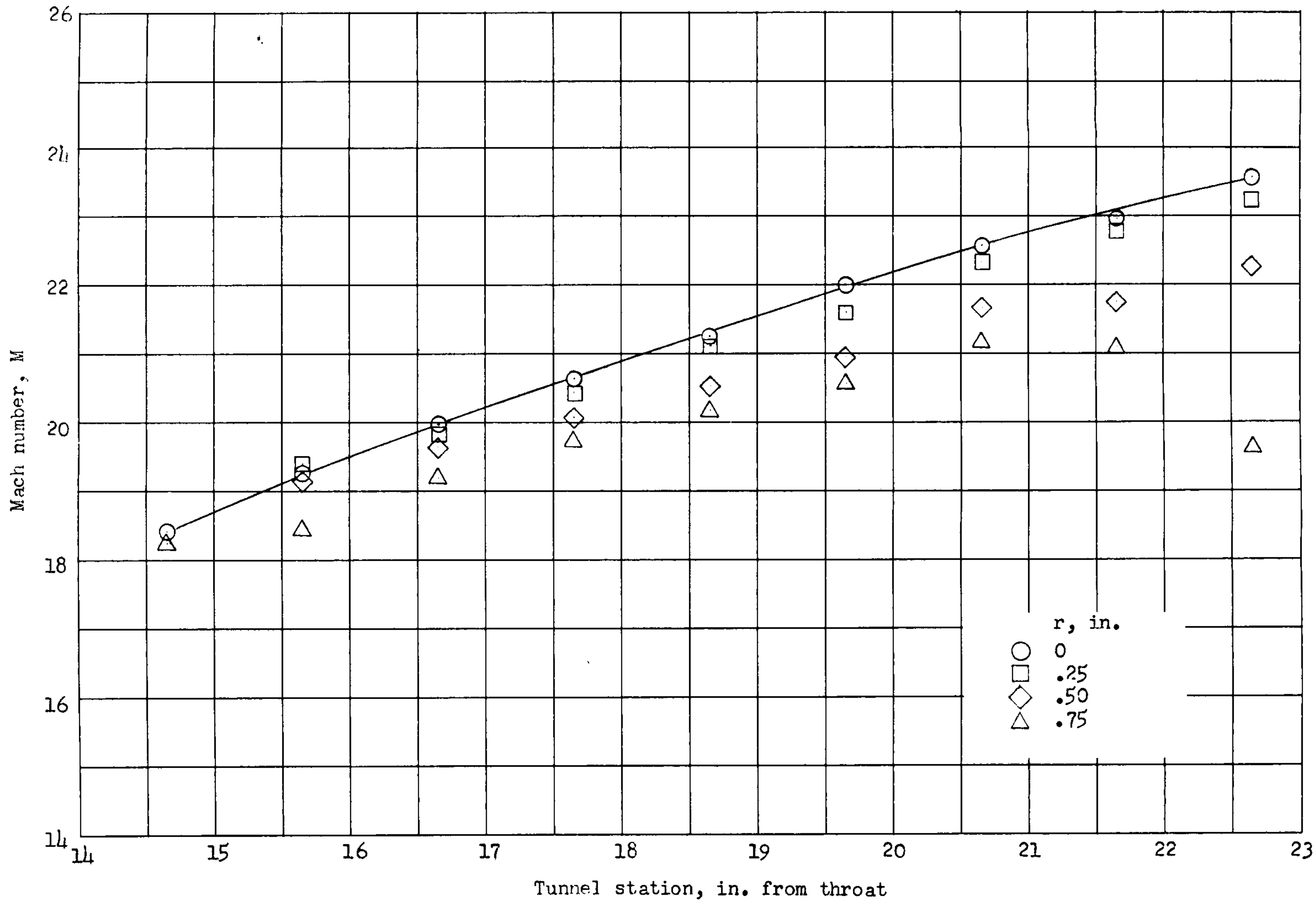

Figure 3.- Mach number distribution in 3-inch helium nozzle. $p_t = 2{,}015$ psia.

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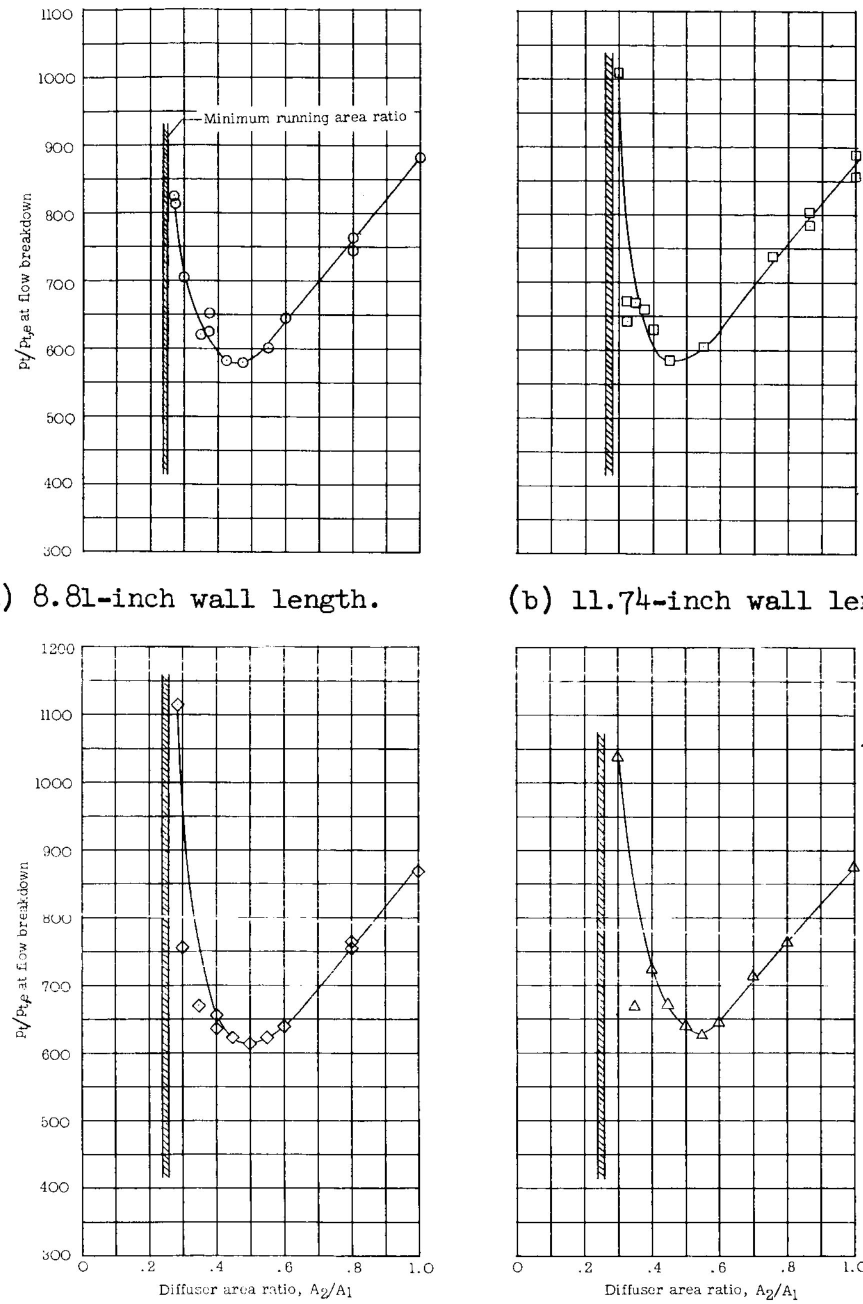

(a) 8.81-inch wall length.

(b) 11.74-inch wall length.

(c) 17.57-inch wall length.

(d) 20.50-inch wall length.

Figure 4.- The pressure ratio across the system required to maintain supersonic flow as a function of diffuser area ratio.

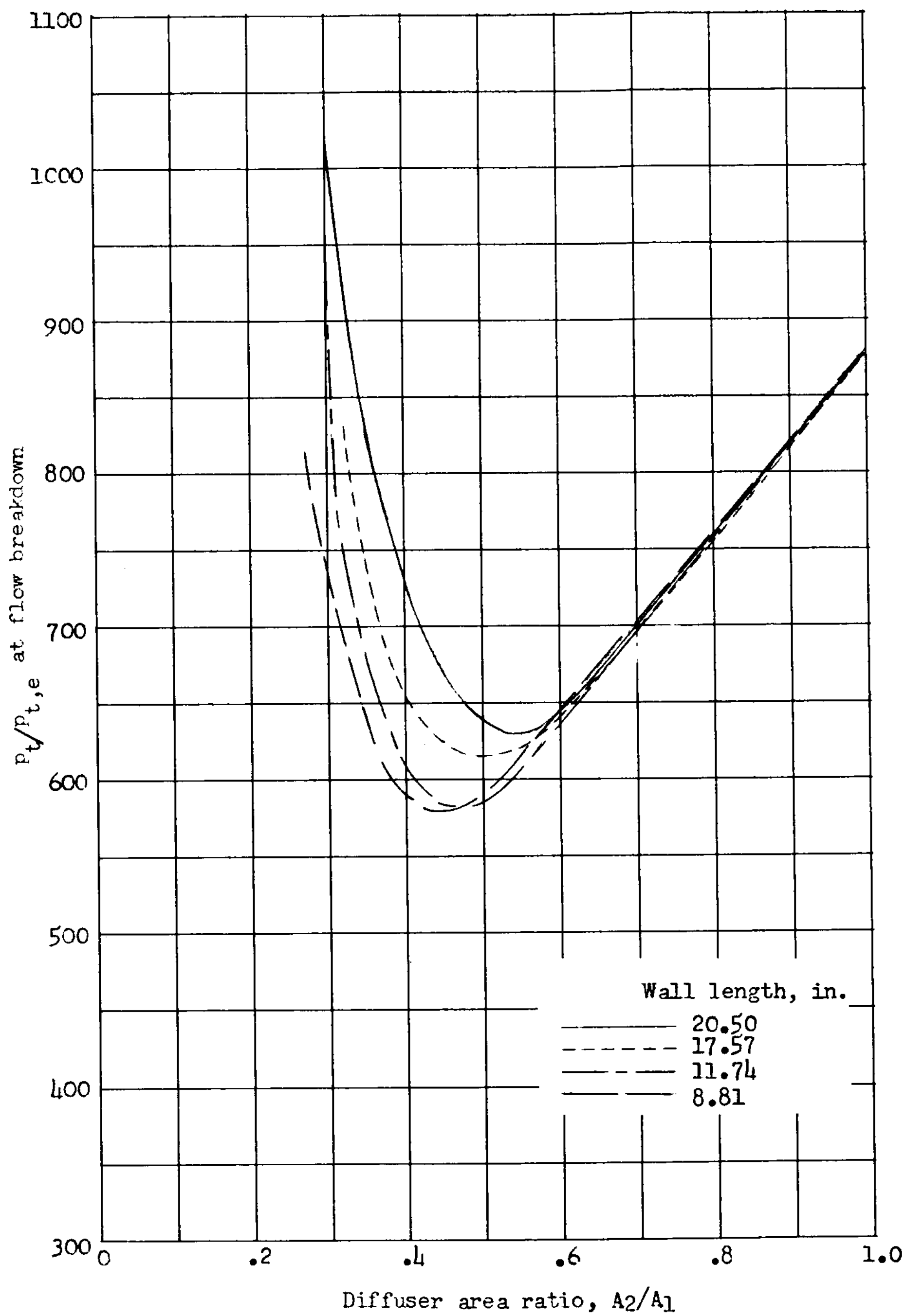

Figure 5.- The pressure ratio across the system required to maintain supersonic flow as a function of diffuser area for each of the four diffuser configurations tested.

L-107

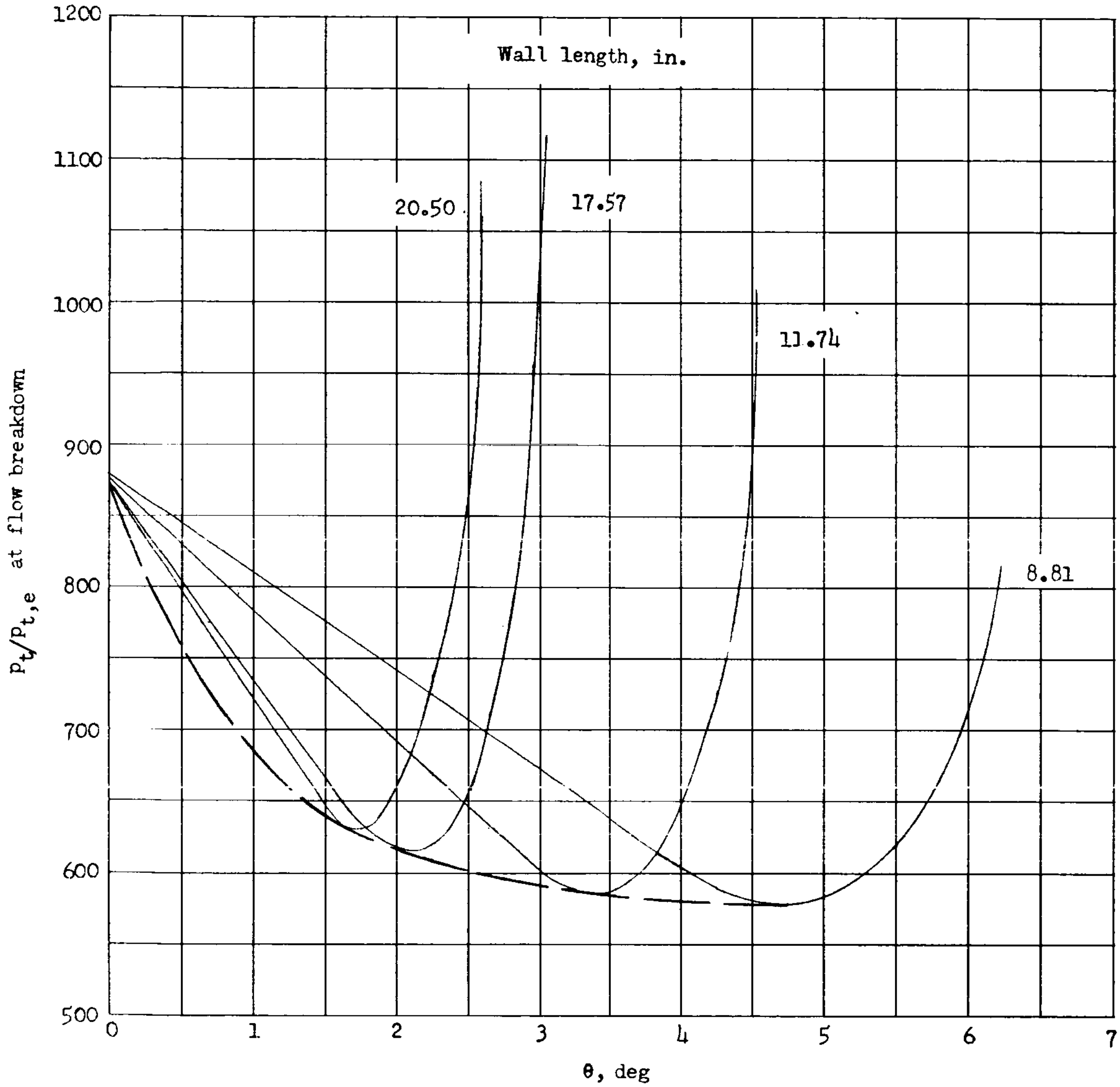

Figure 6.- The pressure ratio across the system necessary to maintain supersonic flow as a function of diffuser entrance wall angle θ.

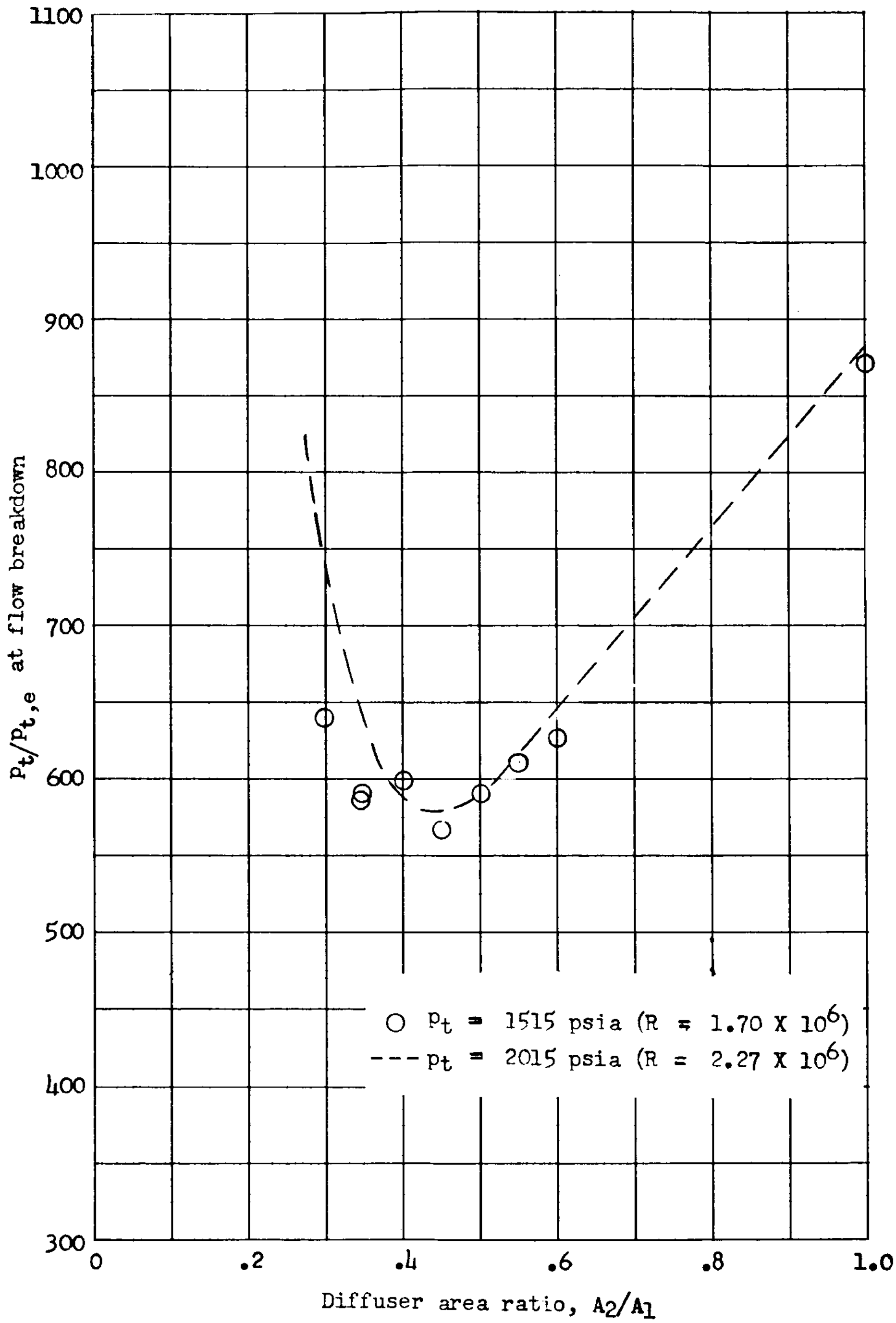

Figure 7.- Effect of Reynolds number on the pressure ratio across the system necessary to maintain supersonic flow. Wall length = 8.81 inches.

L-783

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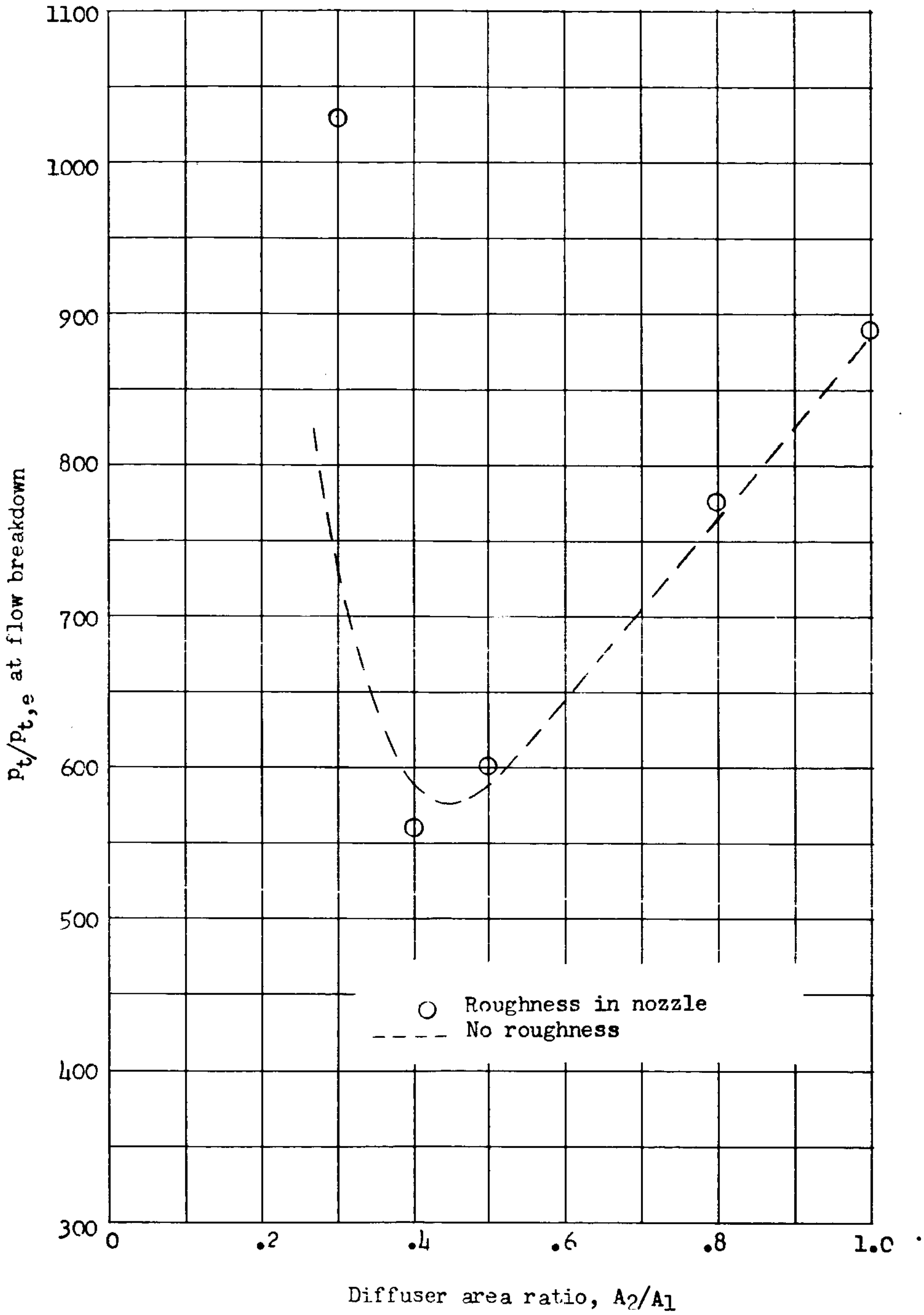

Figure 8.- Effect of roughness in the nozzle on the pressure ratio across the system necessary to maintain supersonic flow. Wall length = 8.81 inches; p_t = 2,015 psia.

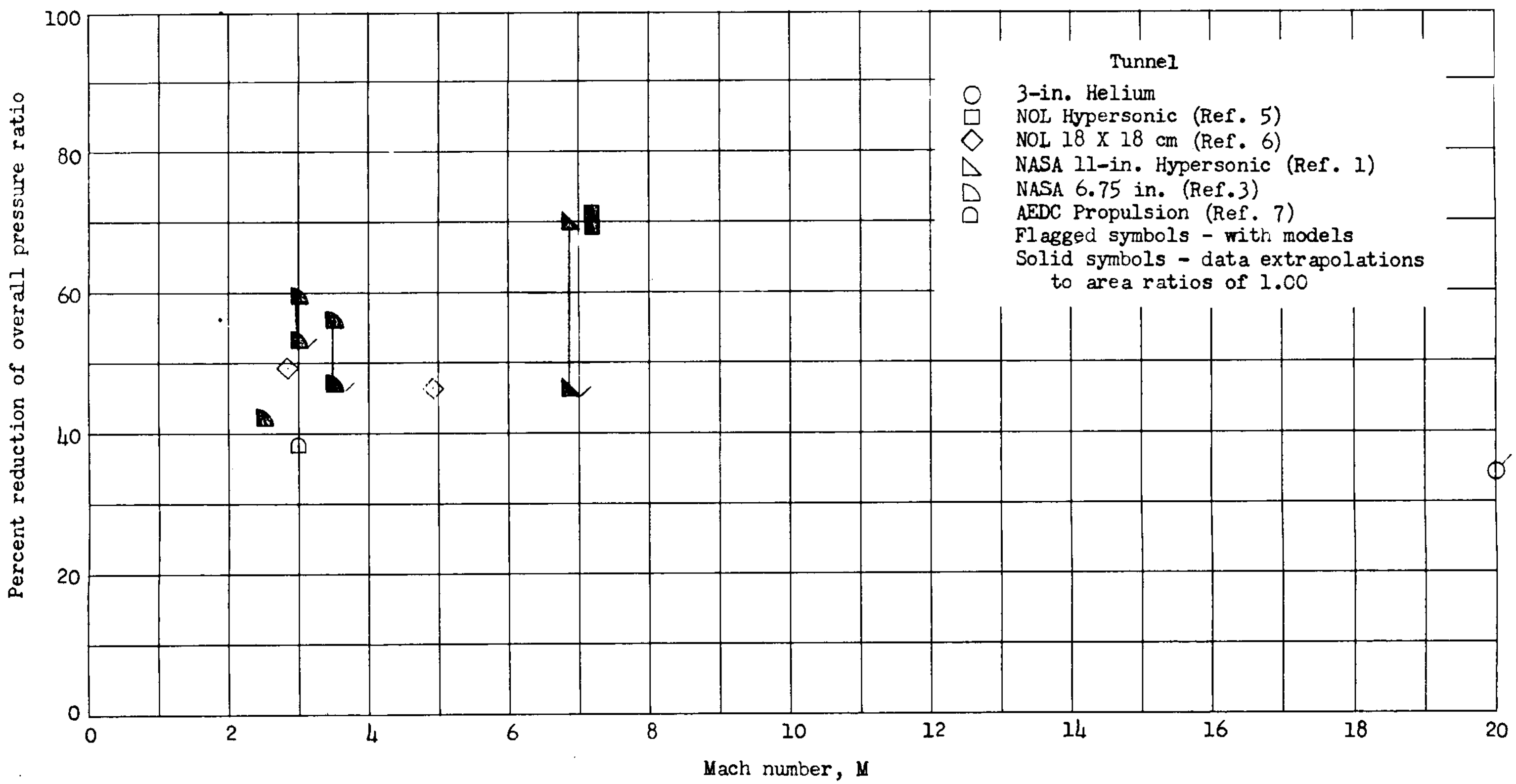

Figure 9.- Percent reduction of overall pressure ratio achieved by the use of a variable-area diffuser as a function of test-section Mach number.

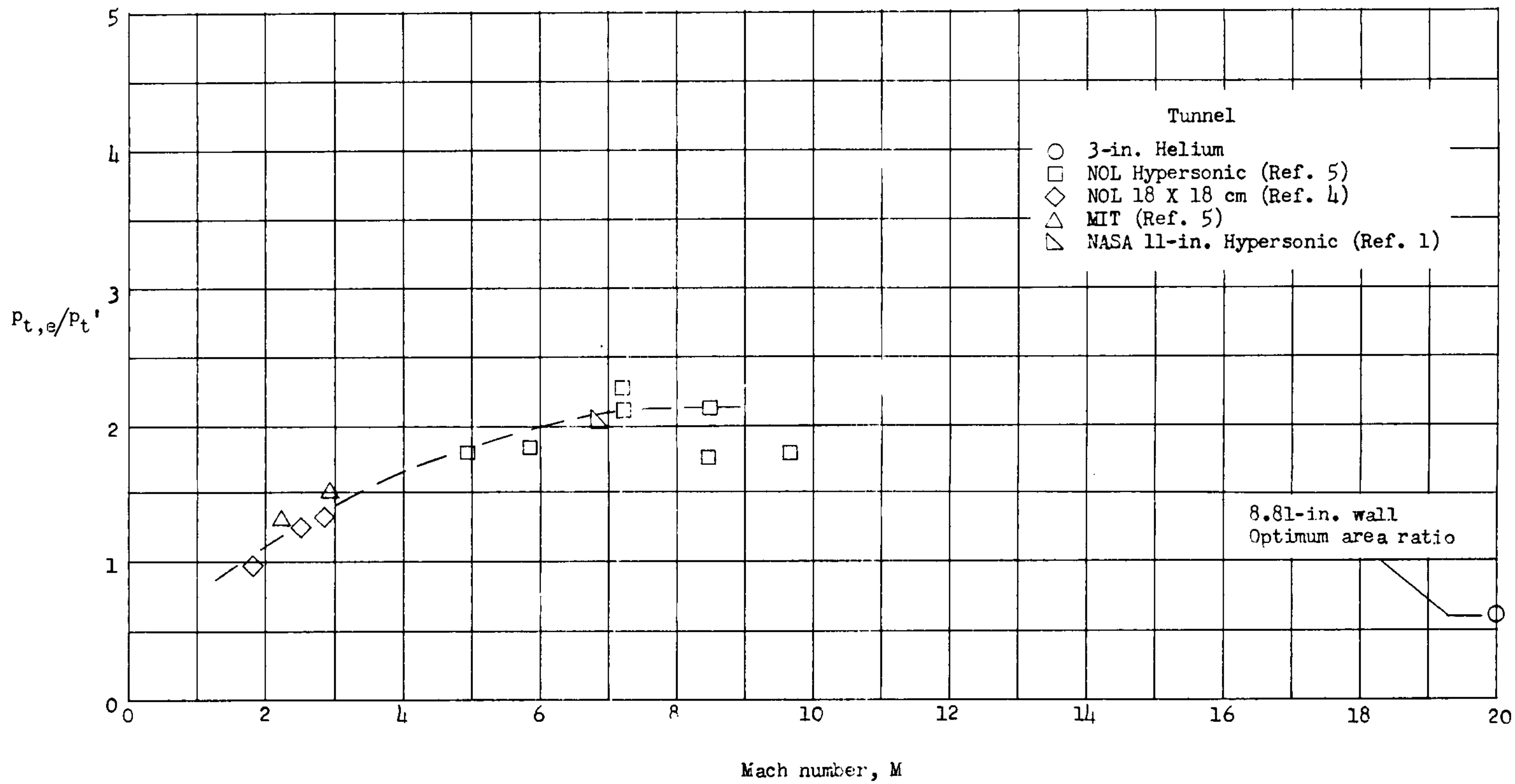

Figure 10.- Effect of Mach number on the pressure recovery of wind tunnels equipped with variable-area diffusers.

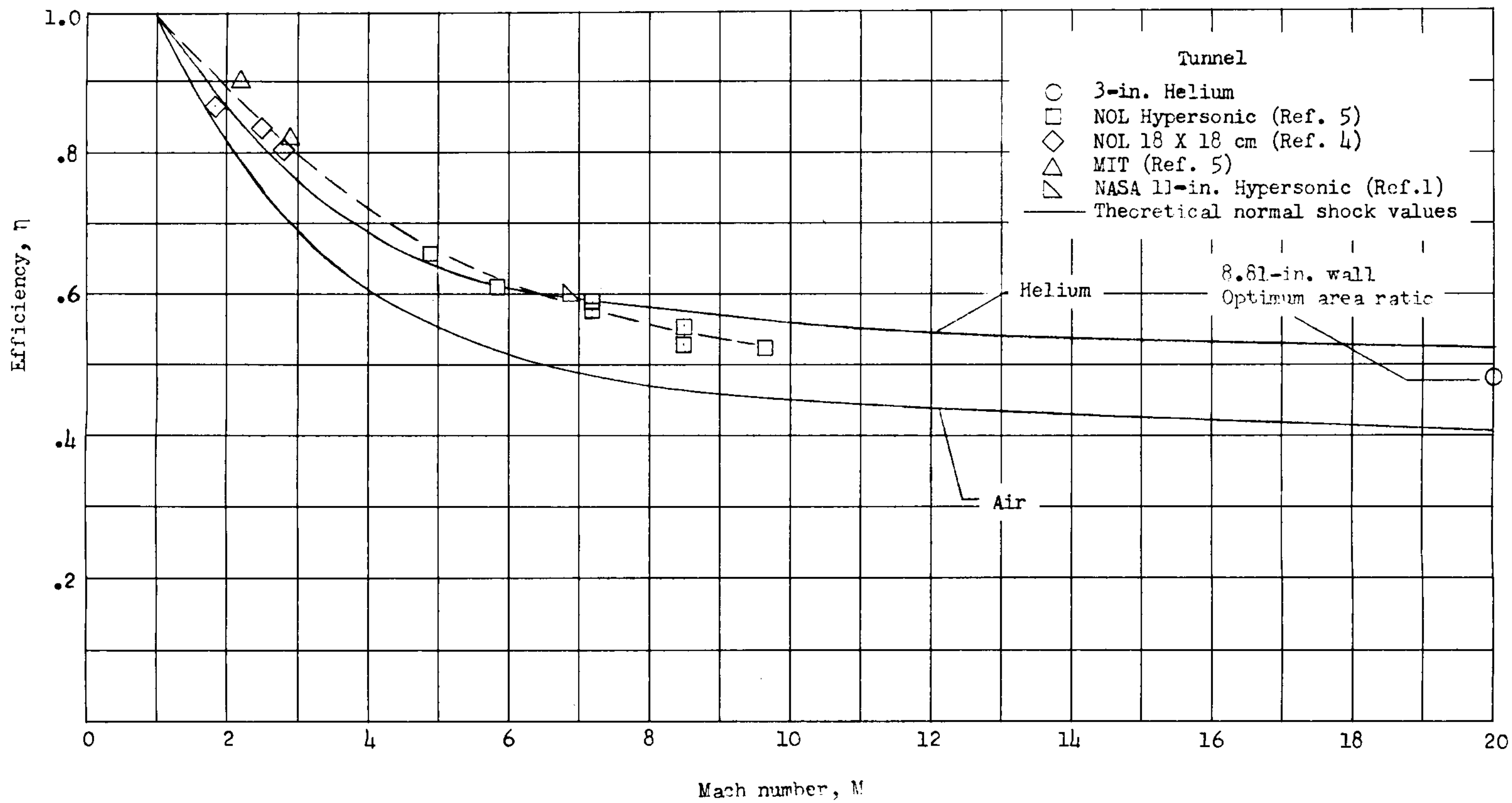

Figure 11.- Variation of diffuser efficiency η with Mach number for wind tunnels equipped with variable-area diffusers.

L-783